NASA TECHNICAL MEMORANDUM

NASA TM X-67835

STATUS OF THE 2- TO 15-kW_e BRAYTON POWER SYSTEM AND POTENTIAL GAINS FROM COMPONENT IMPROVEMENTS

by John L. Klann and William T. Wintucky
Lewis Research Center
Cleveland, Ohio

TECHNICAL PAPER proposed for presentation at
1971 Intersociety Energy Conversion Engineering Conference
sponsored by the Society of Automotive Engineers
Boston, Massachusetts, August 3-6, 1971

ABSTRACT

System and component tests are continuing. Key components have passed 5000 hr of accumulated operating time. No basic technology problems have been found.

Based on the first system tests in a vacuum chamber, a net efficiency of 0.26 would be obtainable in space at 10 kW of useful electric power output; the specific radiator area would be about 75 ft^2/kW_e. Minor system hardware changes are described which would improve system net efficiency to about 0.30 in the 10- to 15-kW range. Corresponding specific radiator areas would be 65 to 62 ft^2/kW_e.

An advanced Brayton power system operating at a turbine-inlet temperature of 2000° F was considered. If developed, it could offer a system net efficiency up to about 0.35 at its high-power conditions; specific radiator area would drop to about 50 ft^2/kW_e.

E-6314

IN 1966 THE STAFF AT NASA-Lewis Research Center began work on a 2- to 10-kW_e Brayton power system. This work was intended to provide the development of technology for Brayton space power systems in this power range. The power conversion module, or engine, was designed for use in space missions with a radioisotope heat source and a liquid-coolant radiator. Our program goals were (1) to show efficient operation of a single engine over the power output range from 2 to 10 kW; (2) to achieve greater than 25 percent system net efficiency; and (3) to have at least a 5-yr (44,000-hr) operational life.

Results of our first system tests in a vacuum chamber were presented at last year's conference (1, 2, 3, 4, and 5*). In these tests, the engine was electrically heated and was cooled with an auxiliary heat exchanger, or radiator simulator. Our first goal was met in these tests. Operation was confirmed over the design power range (1 and 6). An engine net efficiency of 0.29 was measured at 10.5 kW of useful output. Based on this measured engine efficiency and estimates of heat-source thermal losses, our second goal of greater than 25 percent system net efficiency should be readily achievable (1). We are conducting a series of component and system tests toward the third goal of demonstrating operational life. All tests to date have shown no technology problems that would prevent use of this power system. This paper describes the status of our test programs.

Results of component tests have shown a potential for improved system performance with relatively minor hardware changes. These hardware changes, which could improve efficiency and increase the operational power output range of the engine up to 15 kW, are described. Increased system performance is estimated based on the test data from individual components and the current power system. Further potential system gains from a 400° F-higher turbine-inlet temperature are also examined. This 400° F increase would require some major redesigns and is only academic at this time.

PROGRAM STATUS

Table 1 lists our major test programs and shows the number of accumulated test hours for

*Numbers in parentheses designate References at end of paper.

each. Status is discussed separately for the system, subsystem, and component tests.

SYSTEM TESTS - The first system tests, conducted in the Lewis Space Power Facility, accumulated 2561 hr of power system operation (6). Two BRU's (Brayton rotating units: turbine, alternator, and compressor on a single shaft) were used. An electrical power connector short circuit caused the first BRU to overspeed after 668 hr of operation and interrupted the test. Another BRU was installed, and the test continued to a planned shutdown. This second BRU had been previously operated for 1012 hr in another test and has now accumulated 2905 hr of operation. The BRU's were disassembled, and Dunn (7) reports on their post-test inspection. The BRU with 2905 hr of operation has been reassembled and installed back in the power system. The system is being readied for operation with a space-type radiator with testing scheduled to begin in the second half of this year. Miller, Couch, and Prok (8) describe the radiator design and development program. The test configuration to be installed in the vacuum chamber is shown in Fig. 1. A photograph of the engine itself is shown in Fig. 2.

SUBSYSTEM TESTS - A gas power loop consisting of a BXU and a BHXU (Brayton heat exchanger unit: a gas-to-gas recuperator and gas-to-liquid waste heat exchanger) is in a 20,000-hr endurance test program. Valerino and Ream (9) present the detailed status of this test. As of April 12, 1971, over 5000 hr of test operation had been accumulated. This test has been automated. Macosko and Edkin (10) describe the automatic aspects of this test. Well over 4000 hr of operation have been obtained with no operating personnel in attendance. Also, as part of this test program, motor starting of the BRU was performed. In this startup technique, which is an alternative to gas-injection startups, the BRU alternator is used initially as a drive motor. Gilbert et al. (11), report on this part of the test program.

The electrical subsystem is also being given a 20,000-hr but separate endurance test. Vrancik and Spagnuolo (12) describe this subsystem program. The electrical subsystem includes the engine control and monitoring system, the electrical control package for regulating BRU speed and electrical output distribution, the parasitic load bank, the dc power supply for rectifying alternator output and charging batteries, and two inverters (in the total system, these inverters power two liquid-coolant pump motors). As of April 12, 1971, this subsystem had accumulated almost 4000 hr of vacuum-test operation. This test has also been automated. Over 3700 hr were obtained with unattended operation.

The gas management subsystem is also being tested separately. It consists of the gas supply tank and all of its valves, piping, and instrumentation. This subsystem has a 10,000-hr test program which has been started recently. As of April 12, 1971 over 300 test hours had been accumulated.

COMPONENT TESTS - Some individual components are under contract for endurance testing. One such component is the liquid coolant pump-motor assembly (PMA). The pump-motor requires 400-Hz electrical power. A static inverter operating on a 56 V dc input converts to 400-Hz output for the PMA. The PMA and its inverter at Pesco Products, a division of Borg Warner Corporation in Bedford, Ohio, have completed over 12,000 hr in a 20,000-hr endurance test.

Another component in an endurance test is the dc power supply. This component rectifies part of the BRU's 120-V, 1200-Hz, three-phase output to ±28 V dc. The dc power is used for system control functions, by the inverter for the PMA, and for charging of batteries. This dc power supply at Gulton Industries Incorporated, Engineered Magnetics Division in Hawthorne, California, has completed over 15,000 hr in a 20,000 hr endurance test.

A BRU is at Mechanical Technology Incorporated in Latham, New York, for shock and vibration testing. The BRU will be tested both statically and while it is operating. This program and its tests are just under way. The BRU is the only system component presently planned for this type of testing.

CURRENT SYSTEM PERFORMANCE

Net efficiency and required radiator area of a Brayton space power system were calculated based on the data from the first system tests in a vacuum chamber (6).

System net efficiency is the ratio of electric net power output to heat-source gross thermal power. Thollot, Bainbridge, and Nestor (2) show that about 1.4 kW of power are needed for the electrical components over their operational range. Hence, system net power output was calculated as 1.4 kW less than the measured power at the alternator terminals. Heat-source gross thermal power includes the heat added to the engine working gas and the heat lost from the source. Based on a conceptual radioisotope heat source, thermal losses from a 25-kW source could be held to about 2 kW, or 8 percent. Therefore, in evaluating space system efficiency, the required heat-source gross thermal power was calculated as the measured heat-input to the engine divided by 0.92.

System radiator area needs were calculated based on measured heat loads. Both the primary heat load from the engine waste heat exchanger and the secondary heat loads from the alternator and cold plates were included. The radiator configuration which will be used in our next system tests at the Space Power Facility was assumed. A sketch of this radiator and cooling loop arrangement is shown in Fig. 3. Prime areas were calculated (13) and then increased by 20 percent* to allow for the neglected effects of both coolant-to-surface and tube-to-fin temperature drops.

Figure 4 shows the net efficiency and radiator-area needs of the power system based on the performance of the current engine. Specific radiator areas (the actual area divided by the electric net output) are shown. These changes with power level are for the design engine conditions: working gas, a helium-xenon mixture at the molecular weight of krypton (83.8); turbine-inlet temperature, 1600° F; and compressor-inlet temperature, 80° F. For the radiator calculations, an effective heat-sink temperature for near-Earth orbits of -10° F was assumed.

The symbols in Fig. 4 show the system net efficiency based on test data; the lines are analytical predictions based on a slightly modified Lewis computer program (13). System power output is a function of the heat-source thermal power, the amount of gas within the closed power loop, and the size of the radiator. The engine power range from 1.5 to 10.5 kW corresponds to the design operating range in compressor-outlet pressure, 15 to 45 psia. System net efficiency ranged from 0.12 at 1.5 kW to 0.26 at 10.5 kW. The required heat-source power rating for this output range would be from 12.5 to 40.5 kW_t.

System radiator-area needs are a function of the power level, the liquid coolant flow rate, and the effective heat-sink temperature. The specific radiator areas in Fig. 4 were optimized with coolant flow rate (13). The curve is a locus of minimum values. Specific area drops from 220 ft^2/kW_e at 1.5 kW_e to about 75 ft^2/kW_e at 10.5 kW. The required areas increase continuously from 330 ft^2 to about 790 ft^2 over the output range.

*Detailed radiator analyses have shown that the prime area correction factor for this radiator configuration is between 17 and 23 percent.

COMPONENT IMPROVEMENTS

Although the current Brayton system efficiency is as high as 26 percent, component test results have indicated a potentially higher system efficiency with only minor hardware changes. Also, an increase in maximum output power appears feasible. Each potential component improvement is described here under subheadings. These improvements have not as yet been made in the engine. They are being held as improvement options for inclusion at appropriate points in the overall Brayton technology program.

TURBOMACHINERY - There are four changes which could be made within the BRU. These are augmented alternator cooling, a flow-straightener ahead of the compressor inlet, a reset compressor-diffuser vane, and a modified turbine-exit diffuser.

Alternator Cooling - Statistical data for alternators with similar winding insulation and potting compounds show that a 5-yr life may be expected with a maximum winding temperature of about 400° F. Evans and Meyers (14) show that, in a test of the BRU, 15 kW of alternator output was demonstrated. However, the alternator end-turn winding insulation temperature rose above 400° F. Both component and system test results (3 and 14) have shown that to obtain a 5-yr operating life, the current BRU is limited to an alternator output of about 12 kV-A.

Current alternator cooling is handled by liquid-filled coils. They are helical and wrapped axially around the stator. AiResearch Manufacturing Company, a division of the Garrett Corporation in Phoenix, the BRU contractor, has determined that more liquid-cooling passages can be added within the BRU. This, along with other minor changes, should cool the alternator enough to stay below a 400° F hot-spot temperature up to alternator power outputs of about 16 kV-A. AiResearch is under contract to provide the hardware for this additional cooling.

Flow Straightener - In the Brayton engine, a reducing elbow is located just ahead of the compressor inlet. In this 90° elbow, the 4-in. duct from the recuperator is reduced to 3.5 in. for mating to the compressor.

The first tests on the compressor alone were made with a straight inlet duct. Compressor efficiency at the design equivalent mass-flow rate was about 0.79 with a peak efficiency of 0.82 at a lower value of flow rate. Later tests with the reducing elbow showed a penalty in efficiency. At design flow rate, efficiency dropped by about 0.01, while peak efficiency dropped by about 0.02. As a result, a series of elbow-insert, flow-straightening devices were tested. The best device was found to be a single splitter plate located centrally throughout the elbow. With the splitter, efficiency at design flow rate was back to about 0.79, while peak efficiency was about 0.81 - a loss in peak efficiency of only 0.01 from that of the straight-inlet data.

Compressor Diffuser - As part of the compressor tests, three compressor-diffuser vane angles were studied. These tests were run with the straight-inlet duct. A 3° change in vane angle was found to shift the point of peak compressor efficiency to the Brayton system design equivalent mass-flow rate. Also, peak efficiency increased by 0.01 to 0.83. Hence by adjusting the diffuser vanes for operation at peak efficiency there is a potential gain of 0.04 in efficiency. However, with the use of the elbow splitter, the net gain might be reduced to 0.03 for a compressor efficiency of 0.82.

Turbine Diffuser - Rohlik, Kofskey, and Nusbaum (15) show the early results of tests on the shape of the turbine-exit diffuser. The original diffuser has a conical outer wall with a cylindrical centerbody. This provides an area variation with axial distance that is almost linear. Two other diffusers were designed for a linear change in static pressure with axial distance and were tested. Both improved the diffuser pressure recovery and, therefore, improved overall turbine efficiency. The best shape was found to be a cylindrical centerbody with a contoured outer wall for the needed area change.

At design operating conditions, the overall turbine efficiency with the original diffuser was 0.894. Use of the best diffuser resulted in 0.907 for a gain of about 0.01.

HEAT EXCHANGER - In a contract with AiResearch Manufacturing Company of Los Angeles we have ordered a modified version of the BHXU. This new BHXU will have a larger recuperator core and a finned-tube, gas-to-liquid, waste heat exchanger. Kaykaty (4) shows that the original BHXU performed well and nearly achieved all of its design objectives. The recuperator fell just short of its design heat-transfer effectiveness of 0.95. Its measured effectiveness, at its design system power level of 10 kW, was 0.94. The new BHXU recuperator core surface area was increased by 18 percent to achieve the extra 0.01 in effectiveness. The new BHXU also is designed to operate at much higher gas pressures. This will allow system operation at the higher power levels made possible by the added alternator cooling.

HOUSEKEEPING POWER - It appears that the internal housekeeping electric power needs can be reduced from the present 1.4 to 1.0 kW. Such a decrease could be achieved through a combination of improvements.

Thollot, Bainbridge, and Nestor (2) show a breakdown of the current housekeeping needs. About 1 kW is needed by the dc power supply to operate the engine control system, the 400-Hz pump-motor inverters, and miscellaneous valves and relays. The other 0.4 kW of housekeeping power is used to operate the speed control and voltage regulator and to provide residual power in the parasitic load. The residual parasitic load power is needed by the speed control to accommodate system operating point changes.

The greatest drop in housekeeping needs could come from resizing the liquid-coolant pump, and replacing the 400-Hz motor with a 1200-Hz motor that could be operated directly from the alternator output. The current pump provides a coolant pressure rise of 72 psi; this pressure rise is a conservative value set early in the program and is more than appears necessary. The radiator-coolant-loops for the next system test will need only about a 40 psia head rise. Furthermore, use of a 1200-Hz motor would eliminate the power consumed in the inverter during normal operation.

Other smaller drops in housekeeping power are also potentially available. For example, the signal conditioner power needs could be reduced by about 120 W with the use of new high-efficiency power supplies (2) which are being installed. Through improvements in the BRU speed control and voltage regulator, we may be able to reduce the required residual parasitic-load power. The combined drop in housekeeping power from all improvements would be about 400 W.

IMPROVED SYSTEM PERFORMANCE

Effects of the minor hardware changes on system net efficiency and radiator-area needs were calculated. A summary of the component improvements used in the calculations is presented in table 2. Results are shown in Fig. 5. Solid lines are used to show the net efficiency and specific radiator-area needs of the current system. Broken lines are used to show the combined effects of the minor hardware changes. The design temperatures and gas-mixture were maintained. Over the design compressor-outlet pressure range from 15 to 45 psia, the improved system would provide from about 2.2 to 11.9 kW compared to the 1.5 to 10.5 kW of the current system over the same pressure range. A net output of 15 kW with the improved system would require a compressor-outlet pressure of about 55 psia. Continuous operation at this pressure level would be permissible with the improved system.

Net efficiency of the improved system gained as much as 0.035 over that of the current system. Above about 3 kW, the improved system net efficiency exceeded 0.20. In the range of outputs from 10 to 15 kW, efficiency increased to nearly 0.30. At 2.2 kW_e, the improved system would need about a 13-kW_t, heat source. At 15 kW_e, the heat source required rating would be about 50 kW_t.

Specific radiator area needs of the improved system were about 15 ft^2/kW_e less than those of the current system. At the high power outputs, the improved system radiator need was about 62 ft^2/kW_e. Absolute areas ranged from 315 ft^2 at 2.2 kW_e to about 930 ft^2 at 15 kW_e.

POTENTIAL HIGH-TEMPERATURE SYSTEM PERFORMANCE

The conceptual heat source for the current Brayton system operates at an average outer-surface temperature of about 1800° F. Higher temperature capability may result from the Atomic Energy Commission's "Multi-Hundred Watt Radioisotope Thermoelectric Generator" program. In this program, heat sources are being designed for operating outer-surface temperatures of about 2200° F.

Although the present Brayton system components for 50,000-hr operation are limited to a 1600° F turbine-inlet temperature, effects of an increase to 2000° F were calculated to evaluate its merits for a possible future development. There are no plans for such a power-system change.

The gains of the 400° F increase in turbine-inlet temperature were added to the gains of the improved system with the minor hardware changes. Compressor-inlet temperature was kept at its design value of 80° F.

Figure 6 shows the comparison between performance of the current system and an advanced 2000° F system. The power output range for the advanced system is shifted to higher power levels for the same operating gas-pressure range because of the large increase in available turbine work. The advanced system would produce about 4.2 kW of net output at a compressor-outlet pressure of 15 psia, and 15 kW at 45 psia. Predicted efficiency of the advanced system was 0.22 at 4.2 kW, using to about 0.35 at 15 kW. Heat-source power requirements would be 19 kW_t at 4.2 kW of output and 43.5 kW_t at 15 kW_e.

The combined effect of the temperature increase and the hardware changes resulted in a drop of about 25 ft^2/kW_e in specific radiator area needs from those of the current system. At the high values of power output, the specific radiator area needs of the advanced system would be about 50 ft^2/kW_e.

CONCLDING REMARKS

The staff at Lewis has been and is conducting a progressive series of component and system tests. The program objectives are to provide the technology for Brayton power system developments in general; and to show the technical readiness of the 2- to 15-kW_e Brayton power system for use in space. All test results to date have been encouraging. Key system components have passed 5000 hr of accumulated operating time. In our first system tests in a vacuum chamber, we demonstrated engine operation and performance. Based on these tests, 10 kW of useful power is obtainable at a system net efficiency of 0.26 with a specific radiator area need of about 75 ft^2/kW_e. However, testing is really just beginning. More endurance tests are needed. Our next system test will add a space-type radiator to the engine. Future system testing is needed with a space-type heat source.

Evaluation of minor engine hardware changes has shown an attractive potential gain in system efficiency, power output, and radiator area needs. At net power outputs in the range from 10 to 15 kW, a system net efficiency of nearly 0.30 was predicted. Corresponding specific radiator areas were about 62 ft^2/kW_e.

A 400° F increase in operating temperature level was evaluated for assessing the potential performance of an advanced Brayton power system. The combined changes, temperature and hardware, showed a potential system net efficiency increasing from 0.22 at its low-power conditions up to about 0.35 at its high-power conditions. At 15 kW of output, the specific radiator area needs of the advanced system were about 50 ft^2/kW_e. Currently, there are no plans for developing this advanced system.

REFERENCES

1. J. L. Klann, R. W. Vernon, D. B. Fenn, and H. C. Block, "Performance of the Electrically-Heated 2-to-15 kW_e Brayton Power System." Paper presented at 1970 IECEC.
2. P. A. Thollot, R. C. Bainbridge, and J. Nestor, "Description and Performance of the Electrical Subsystem for a 2-to-15 kWe Brayton Power System." Paper presented at 1970 IECEC.
3. D. G. Beremand, D. Namkoong, and R. Y. Wong, "Experimental Performance Characteristics of Three Identical Brayton Rotating Units." Paper presented at 1970 IECEC.
4. G. N. Kaykaty, "Design Description and Performance Test Results from Two Identical Brayton Heat Exchanger Units." Paper presented at 1970 IECEC.
5. R. L. Thomas, R. S. Bilski, and R. A. Wolf, "Requirements, Design, and Performance of a Control System for a Brayton Power System." Paper presented at 1970 IECEC.
6. R. W. Vernon and T. J. Miller, "Experimental Performance of a 2-to-15 kW Brayton Power System Using a Mixture of Helium and Xenon." NASA TM X-52936, 1970.
7. J. H. Dunn, "Post Test Inspection of Three Brayton Rotating Units." Paper presented at 1971 IECEC.
8. T. J. Miller, J. P. Couch, and G. M. Prok, "Design and Preliminary Testing of a Brayton Space Radiator Concept." Paper presented at 1971 IECEC.
9. A. S. Valerino and L. W. Ream, "Performance of the Major Components Operating in a Closed Loop 2-15 kW Brayton Power System." Paper presented at 1971 IECEC.
10. R. P. Macosko and R. A. Edkin, "Experience with Automated Endurance Testing a Brayton Power Conversion System." Paper presented at 1971 IECEC.
11. L. J. Gilbert, R. J. Frye, J. S. Curreri, and D. A. Cantoni, "Motor Start Techniques for 2-to-15 kW Brayton Space Power System." Paper presented at 1971 IECEC.
12. J. E. Vrancik and A. C. Spagnuolo, "Experimental Evaluation of the Electrical Subsystem of the 2-to-15 kW Brayton Power Conversion System." Paper presented at 1971 IECEC.
13. J. L. Klann, "Steady State Analysis of a Brayton Space Power System." NASA TN D-5673, 1970.
14. R. C. Evans and S. J. Meyer, "Electrical Performance of a 2-to-10 kW Brayton Rotating Unit," NASA TM X-2062, 1970.
15. H. E. Rohlik, M. G. Kofsky, and W. J. Nusbaum, "Radial Inflow Turbine Performance with an Exit Diffuser Designed for Linear Static Pressure Variation." NASA TM X-52870, 1970.

Table 1 - Brayton Project - Major Test Record as of April 12, 1971

Tests	Starts (or cycles)	Accumulated test hours
System test in Space Power Facility		
With BRU-1A	9	668
With BRU-2	4	1893
Total	13	2561
Gas power loop		
BRU-3, BHXU-1	1	3
BRU-4, BHXU-1	71	5382
Total	72	5385
(unattended)		(4625)
Electrical subsystem		3938
(unattended)	72	(3717)
Gas management subsystem	8	302
Pump motor and inverter	(68)	12,372
dc power supply	(89)	15,184

Table 2 - Summary of Component Improvements

Component parameter	Current system	Improved system
Compressor efficiency	0.79	0.82
Turbine efficiency	0.89	0.90
Recuperator heat-transfer effectiveness	0.94	0.95
Housekeeping power needs, kW_e	1.4	1.0

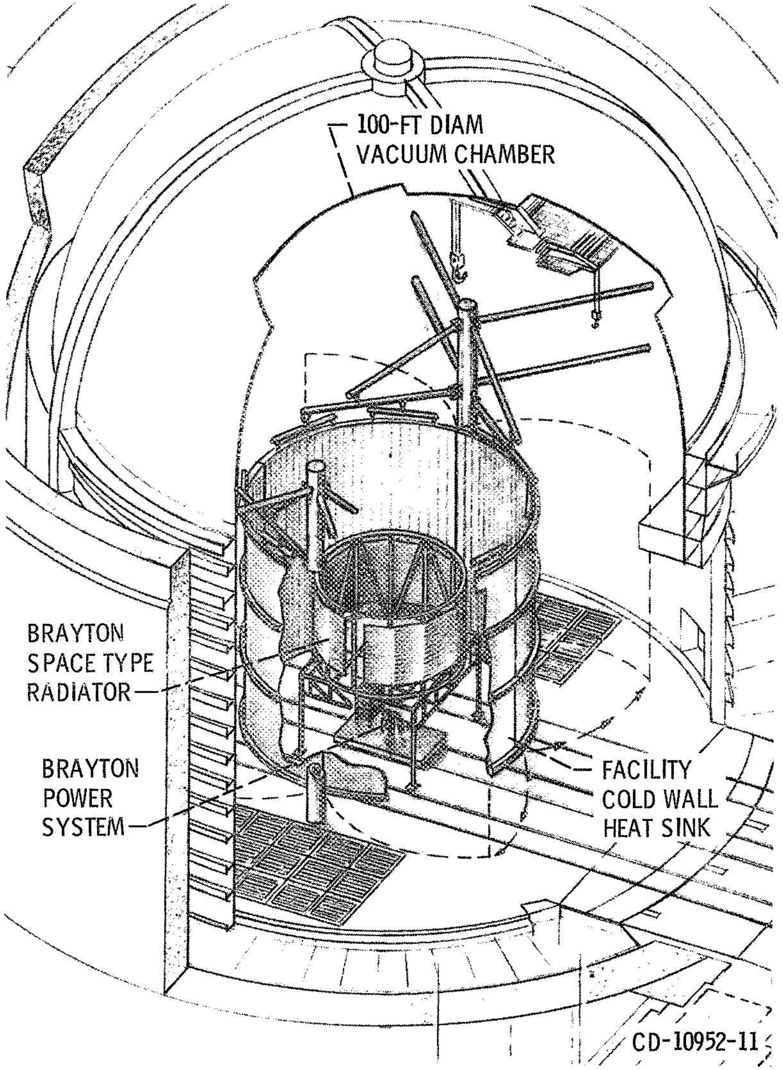

Figure 1. - Brayton power system test in Plum Brook space power facility.

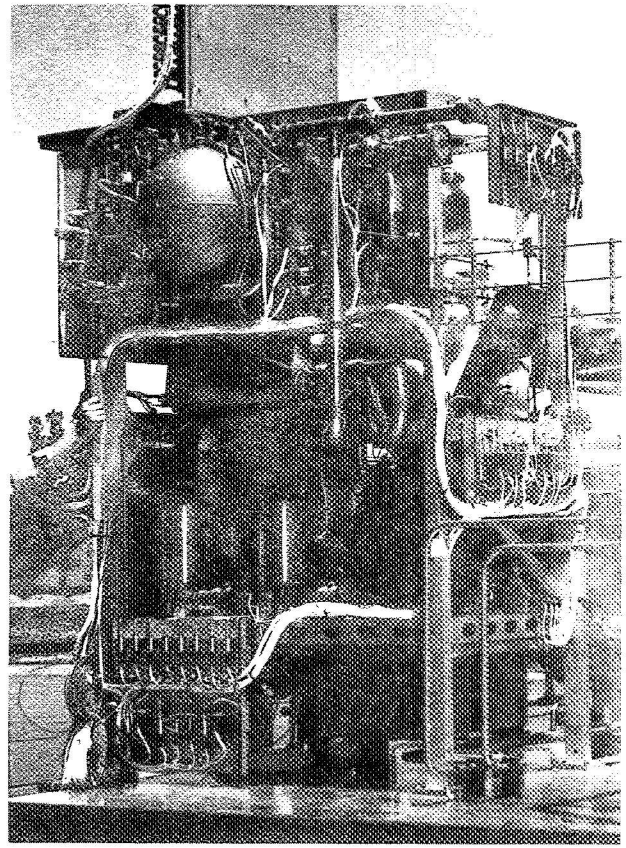

Figure 2. - Brayton engine.

E-6314

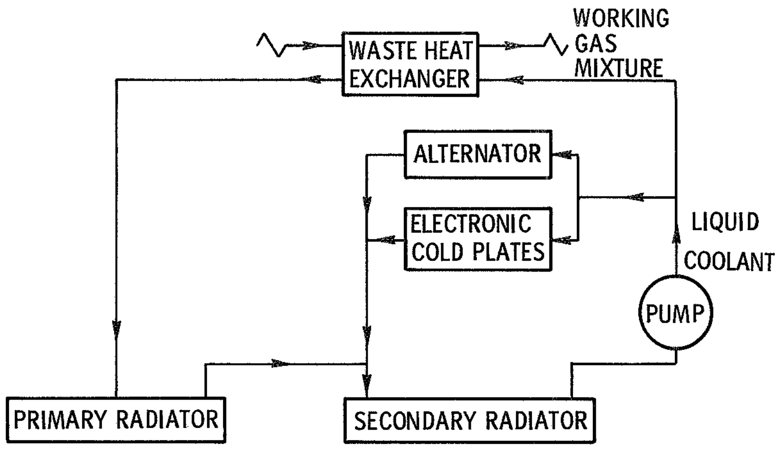

Figure 3. - Sketch of radiator and cooling-loop arrangement.

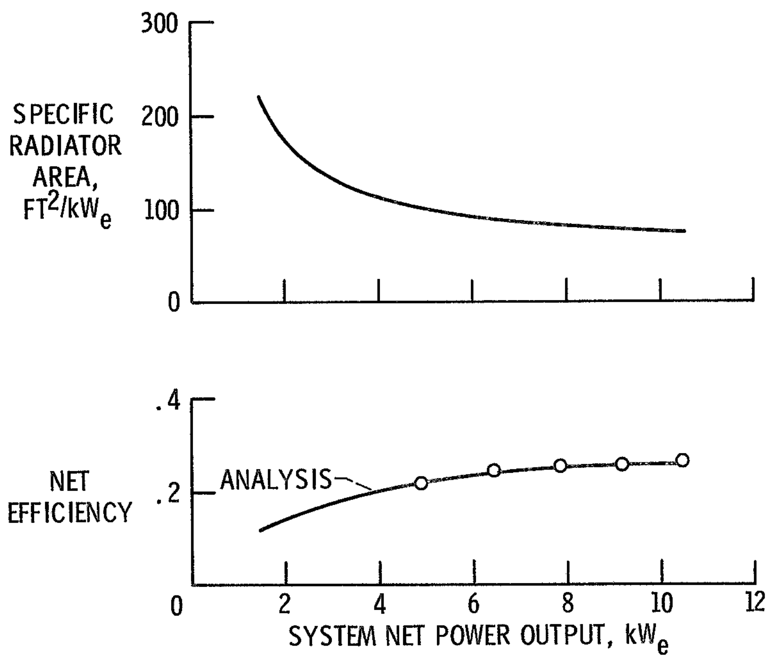

Figure 4. - Efficiency and radiator-area needs of current Brayton power system; turbine-inlet temperature, 1600^0 F; compressor-inlet temperature, 80^0 F; effective radiator heat-sink temperature, -10^0 F.

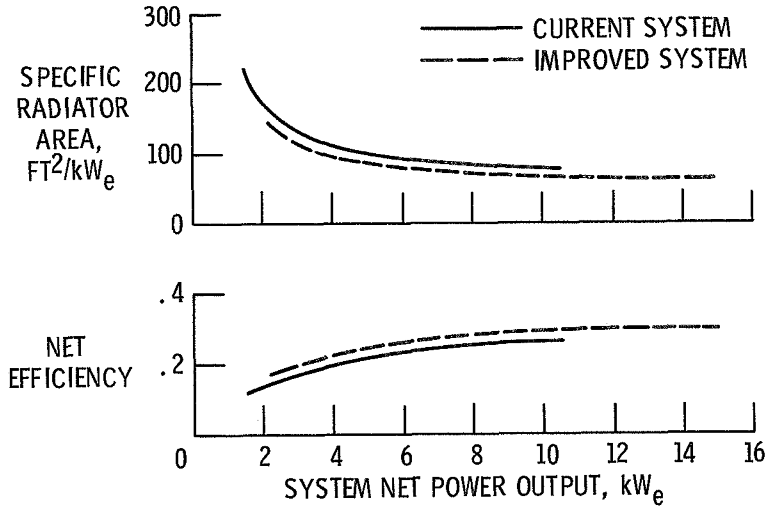

Figure 5. - Effect of minor hardware changes on power system performance; effective radiator heat-sink temperature, -10° F.

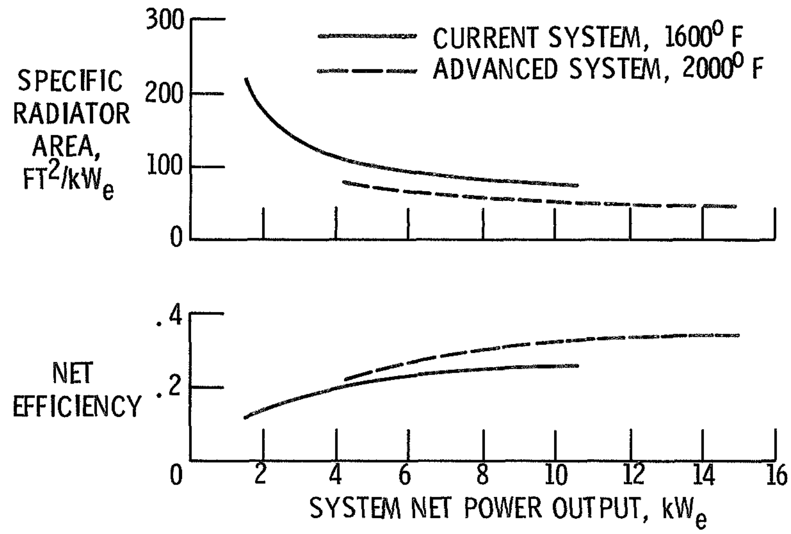

Figure 6. - Added effect of higher temperature on power system performance; effective radiator heat-sink temperature, -10° F.